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How can Virtual Reality and Augmented Reality Support the Design Review of Building Services

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ABSTRACT: *Cost overrun, failure and defect in civil engineering are known problems, which among other things are caused by increased complexity, more rigorous requirements for the building services, indoor environment and building energy performance. Existing design and design review are primarily based on 2D drawings and descriptions and less on 3D models, which places demand on human interpretation. Virtual reality (VR) and augmented reality (AR) are technologies that allow a user to experience a computer-generated environment or add virtual models and information as a layer on top of the physical world. These technologies make it possible to inspect building design proposals as intuitively as in a real building and with minimal need for interpretation. Research from the manufacturing industry shows that the quality and productivity can increase significantly with the aid of VR and AR. The aim of this study is to identify possibilities for new VR and AR supported design review processes, that potentially can improve the quality of building services. This paper reports an interview-based qualitative study, where five representatives from different parts of the Architecture, Engineering and Construction (AEC) industry in Denmark were asked to go in to detail about 1) failure and defects, 2) traditional design review and VR and AR supported design review. This study showed that VR supported design review can potentially replace a physical mock-up and be suitable in the design phase, especially when reviewing constructability. Furthermore, AR supported design review clearly has a potential in the construction phase. It is suggested that the VR and AR supported design review take place in the existing design review processes. Furthermore, an information filtering process in the VR and AR setup, that is controlled by the project's type, complexity and users, is suggested.*

KEYWORDS: *Augmented Reality, Virtual Reality, Design Review, Building Services, Failures and Defects, Information Filtering.*

1. INTRODUCTION

A construction project is considered successful if the construction is done on time, at agreed price and quality, and achieves a high degree of customer satisfaction. Unfortunately, there are many examples of this not being achieved (Akin, 2011; Shirkavand, Lohne and Lædre, 2016). It is the impression of the authors, as well as Shirkavand et al. that problems with delays, failure and defects are, among other things, due to increased complexity and increasing demands from the building services, indoor climate and energy performance. The purpose of this paper is to identify new processes for design review, based on VR and AR, that can improve the quality of building services.

In 2008-2012, an examination of the constructional documentation regarding 100 buildings in Denmark was carried out, which showed that the average fulfilment of requirements was 43% (Hansen and Aagaard, 2013). At the same time, failures and defect is estimated to account for up to 10% of the total costs in the Danish construction sector (Statens Byggeforskningsinstitut, 2004). Shirkavand et al. find that defects related to building services is the area with most frequent negative deviations. Furthermore, they find that the main reason is incomplete or poor design (Shirkavand, Lohne and Lædre, 2016). Inadequate or improper execution of building services entail, that they cannot maintain the desired indoor climate, or they will provide the desired indoor climate with a considerably higher energy consumption than intended (Construction Products Association, 2016).

For decades, analyses of the AEC industry have uncovered low productivity development compared to other industries and other countries. Among other things, the Danish Ministry of Higher Education and Science points out the need for research in manufacturing processes and cooperation between the parties involved as a solution to lack of growth in the AEC industry (Schrøder, 2016). Design and planning of buildings and especially their building services is a complex process, since buildings are unique, the parties are many and different from project to project. In addition, several of the parties, such as users and building owner, are not necessarily building professionals. The current design, design review and execution processes are largely based on 2D drawings, descriptions and to a lesser extent on 3D models, which is inadequate (Thuesen and Ryesgaard, 2018) and a

demanding cognitive load (Hou, 2013). When using VR and AR it is possible to obtain a more natural and intuitive design review, like that performed in constructed buildings. These years access to VR and AR is moving from a narrow professional market to the wide consumer market. This transformation creates an accessibility and development that makes a broad use in the AEC industry, natural even for smaller companies. Experience from the manufacturing industry shows that quality and productivity can be significantly enhanced by these technologies (Hou and Wang, 2013; Rios *et al.*, 2013; Richardson *et al.*, 2014; Hou, Wang and Truijens, 2015; Wolfartsberger, 2019).

Based on the manufacturing industry's positive results, the question is raised, whether this can also be achieved in design review processes of building services. However, due to a building project's long, interdisciplinary and complex process, it is not obvious if, when or how VR and AR can provide value to the design review process of buildings. Resent research have investigated the potential of the technologies in the AEC industry, which indicate that they have a potential of enhanced productivity, shortened project duration, reduced conflicts, improved project collaboration, and reduction of rework (Bademosi and Issa, 2018). Nevertheless, one of the main risks is the extent that the technology is ready to be used in the AEC industry (Heinzel and Azhar, 2017).

This paper reports an interview-based qualitative study, where five representatives from different parts of the AEC industry in Denmark were asked to go in to detail about 1) failure and defects, 2) traditional design review and 3) VR and AR supported design review. The aim is to identify new VR and AR supported design review processes, that potentially can improve the quality of building services. This knowledge is important to target the development of methods and tools that gives value to the AEC industry.

2. METHOD

The aim of this study is to identify new possibilities for VR and AR supported design review processes. To clarify this research domain, a series of semi-structured interviews were conducted, which can uncover rich descriptive data on the personal experience of the participants (Zorn, 2008). Furthermore, the information gathered can move the process from a general topic (domains) to more specific insights (factors and variables). Following William C. Adams guidelines (Adams, 2015), the design of the semi-structured interviews was based on an inductive approach, where the questions were open and investigating, following the three following topics:

- Topic 1: Failure and Defect in the AEC Industry
- Topic 2: Traditional Design Review of Building Services
- Topic 3: Virtual- and Augmented Reality based Design Review of Building Services

The interviews were conducted in connection with The Digital Days (DD), which is a 3 days convention within AEC that focuses on digital collaboration, -technologies and -communication (De Digitale Dage, 2018). During DD, students from UCN and Aalborg University create digital construction projects with guidance from experts from the Danish AEC industry. Out of all the participating experts only a few had experiences with building services, which was crucial for this study. Furthermore, the experts' knowledge and experience within AR and VR was diverse. Therefore, prior to the interview, the experts were introduced to the technologies. They were presented to a simple student 3D model in VR, see Fig. 2, and were shown an introduction video of AR, see Fig. 1.

In spite of the fact that the experts' knowledge and experience within AR and VR technologies in some cases were at a novice level, they were able to provide a practice-oriented knowledge within traditional and new possibilities for design review processes, which is the main purpose of the study. Five of these participants were selected for the interview, see Table 1, which, in our opinion, was sufficient to give an idea of how VR and AR can support design review of building services. However, a larger number of interviewees would increase the generalizability of the study and improve the validity of making general conclusions.

The interviews where first recorded and later transcribed. The transcribed interviews were then condensated into sub-topics emerging from the data on three different levels, following a grounded theory approach (Strübing, 2007). 1) Open coding: Going through each sentence and marking keywords and sentences, in which clearly illustrates the expert's opinion in relation to the problem area. 2) Axial coding: Common features from the different experts is identified and categorized. 3) Selective coding: Generalizing the identified categories into themes.

Table 1: Background of the interviewed participants. Scale: Novice, Advanced, Competent, Skilled and Expert

No	Background	Present occupation	VR	AR	Building Services	AEC industry
1	M.Sc. in CMBI[1]	Developer	Skilled	Skilled	Advanced	4 y
2	P.Ba. in ATCM[2]	Eng. Consultant	Competent	Advanced	Advanced	7 y
3	P.Ba. in ATCM[2]	Contractor	Novice	Novice	Competent	10 y
4	P.Ba. in ATC[2]	Eng. Consultant	Competent	Advanced	Advanced	6 y
5	M.Sc. in CE[3]	Eng. Consultant	Novice	Novice	Expert	15 y

[1] CMBI: Construction Management and Building Informatics
[2]ARCM: Architectural Technology and Construction Management
[3]CE: Civil Engineering

3. RESULTS

This section consists of three subsections, which present the results from the semi-structured interviews with the experts from the AEC industry. The sections summaries the prevailing answers and main tendencies from the interviews, in relation to the three themes mentioned above. The interviews are also summarized in Table 2.

Table 2: Summarization of the interviews, where Axial codes and selective code based on the open codes

Open code	Building services; Routing; Installation room; Project complexity; Poor execution; Poor design; Lack of time; Interdisciplinary collaboration; Non-disciplinary	Design phase; Construction phase; BIM; 2D drawings; Mock-up; Interdisciplinary collaboration; Non-disciplinary; Regular meetings; Collision control; Coordination	Comprehend ability; Constructability; Intuitively observation; Abstract level; Accessibility; Information level; User type; Complexity; Information management; Traceability
Axial code	Failure and defect	Traditional design review	AR and VR supported design review
Selective code	Improving design quality of building services in AEC industry		

3.1 Failure and Defect in the AEC Industry

As stated in the introduction, failures and defects in the AEC industry are well-known problems. In this subsection, the experts were asked to comment on this problem in relation to their own practice as well as in general.

3.1.1 To what degree are failures and defects actual problems?

The five experts agree that failures and defects in the Danish AEC industry are genuine problems. As a matter of fact, four experts directly state that it is a huge problem. The issue has existed for a long time and has not decreased over time, according to expert no. 5. On the contrary, he states that the problem has especially increased in public projects.

The experts also agree that the problem is often related to the building services. The experts appoint installations room, shafts, suspended ceiling and branch points in general as being typical places of attraction. When asked, to what degree are failures and defects an actual problem, expert no. 3 replied:

"A big problem. I have been involved in projects where building services clash in the suspended ceiling, which is the primary place where things go wrong"

Especially in complex building projects where there are few repetitions, the amount of failures and defects increases. It is implicit that with unique complex buildings, the above-mentioned building services also become more complex. As opposed to simple apartment buildings, were building services is monotonous with many repetitions. Expert 3 explains:

"In student apartments, where the setup is fairly simple, the risk for defects is not particularly high, because when you have built one apartment, you have already defined the rest of them"

3.1.2 Why do failures and defects arise?

It is important to note, that failures and defects arise both during the design phase and the construction phase. In some cases, mistakes are made in the project material by the design team, where in the worst-case failures and defects are first discovered in the construction phase. As in other cases, mistakes are made in the construction phase, even though the project material is correct. In general, the experts agree that the overall reason for failures and defects is lack of time. In this subsection, both failures and defects are investigated more thoroughly.

It is important to note that in a turnkey contract, which is the most commonly used contract form in Denmark at the time, the subcontractors are not known until the project material is defined. It's on the very basis of this project material that the subcontractors make an offer. In most cases, the turnkey contractor will pick the lowest bidding, in order to save money. In some cases, the turnkey contractor will stick to the engineering consultant's project material, in that way failures and defects in the design, if any, are not his responsibility. In other cases, the turnkey contractor will give the subcontractor a certain freedom to carry out his work, in that way the contractor will get the cheapest solution.

Generally, all experts agree that one of the main reasons that failure and defect arise, is the lack of collaboration between the different parts of the AEC industry as well as interdisciplinary collaboration between the different disciplines within building services, such as heating, ventilation, plumbing etc. In the design phase it is common for the designer to focus his work within his own discipline, e.g. ventilation. Expert no. 2 explains a typical situation:

"When designing cable trays, one is not typically looking at ventilation channels, which results in a collision"

Expert no. 2 continues explaining, that when a designer does not know how to solve a routing problem, he will intentionally create a collision, because he knows it will be solved later in a collision meeting. The drawback is that it can be time consuming to rectify the flaws.

In relation to the construction phase, expert no. 4 mentions that especially in shafts and in suspended ceilings, where cored-out openings in concrete elements define the routing for building services, the first subcontractor (e.g. ventilation) interprets this as the fastest and cheapest for himself, which later makes a challenge for the other subcontractors. Similar tendencies are also described by the other experts.

With the exception of major contractors, the design review and execution processes in construction phase is based on 2D drawings, even though the building is designed in 3D by the use of Building Information Modelling (BIM). Two of the experts argue, this entails loss of information as well as requires increased knowledge of building services of the persons involved. Furthermore, in order to keep the drawing simple, such a 2D drawing will typically only contain information on one discipline, making it difficult to coordinate in relation to other disciplines.

Coring-out concrete elements for building services routing is time consuming. Today it is common that cored-out openings in concrete elements is done in the production, saving a lot of time on the construction site. However, due to the long waiting list and production time of the concrete elements, these openings need to be fixed quite early in the designing phase, which appears to be very difficult.

3.2 Traditional Design Review of Building Services

In the AEC industry it is common practice to go through design reviews in both the design and construction phase. There are many aspects of design review, such as an informal review of the ventilation system by the designer himself, internal design review of the whole and/or parts of the building service systems as well as design review of the whole building service systems by all/different parts of the AEC. In this subsection traditional design review methods are investigated.

3.2.1 How is design review in the design process performed?

Today the majority of design teams, such as architects and engineering consultants, design buildings in 3D by use BIM as opposed to computer aided design. To a degree, depending on the level of information, BIM allows the designer to create a digital copy of a building.

Typically, when a designer, e.g. ventilation engineer, designs the ventilation system, he will only relate to his own discipline, since anything else will be difficult to comprehend. This especially applies in complex buildings. This often result in defects such as collisions between various parts of the building services. Today it is common that the design team organizes regular meetings, typical weekly, where these collisions are solved. In a turnkey contract, it is common that the contractor attends these meetings if and when needed. According to expert no. 4, it is often at these meetings most failures and defects in the design is discovered.

Design reviews is based on the 3D model as well as the information the model contain. Expert no. 4 finds that collisions are typically found automatically by software, such as Solibri, and attended to at the above-mentioned meetings. However, expert no. 2 points out that constructability is not solved by this software. He states:

> *"Collision contlrol software is not more intelligent than the person sitting behind the screen, in that way a person could easily model something that is not constructible, without it being detected by the software"*

3.2.2 How is design review in construction phase performed?

As mentioned in subsection 3.1.1. most contractors perform design review on the basis of 2D drawings. Typically, the contractor arranges design review meetings on a regular basis, where the consulting engineer and subcontractor(s) participate. Here they coordinate workflow so that everyone knows how and when an agreed task is executed.

In order to perform a thorough design review, expert no. 3 mentions that they build a physical mock-up of the problematic rooms, e.g. installations room etc. In that way they can get a spatial understanding as well as review a com plex solution. The expert underlines that this is an expensive solution, however, he also states that it is an efficient method to achieve constructible solutions.

During the construction phase the engineering consultants also go through a design review of the building services in the construction phase. This is to make sure that the building services are installed according to the design.

3.3 Virtual Reality and Augmented Reality supported Design Review

As described in the section METHOD, the experts where introduced to AR, se Fig. 1, as well as experienced VR, se Fig. 2. In this section, a VR and AR supported design review is investigated, followed by the section DISCUSSION, where a suggestion to how VR and AR can support the design review of building services.

Fig. 1: (Left) AR view of ventilation system in a meeting room. (Right) Viewpoint of the user. This picture is a screen shot from an AR demonstration video from a student project at Aalborg University

3.3.1 Can VR and AR supported design review be of value for the AEC industry?

All the interviewed experts agree that VR and AR technologies have great potential, however the problem is to identify how these technologies bring value. As expected, the experts fully agree that VR has its potential in the design phase, since most projects today are already designed in a fully compatible digital model. Furthermore, the experts agree that AR has its potential in the construction phase, since AR makes it possible to display the digital model augmented on the real building.

Expert no. 2 and 4 argue that designing and design review in 3D is an efficient method to reduce failures and defects. However, they do not entirely agree that VR would be better suited than a traditional design review in a BIM software, such as Revit. They present 3 main arguments: 1) Collision control is already done automatically, 2) it's important to work in 3D view and simultaneously keep track of ones position in a 2D plan and 3) during the weekly interdisciplinary meetings of the design team, it is important to be able to see the same view on the screen and have eye contact when discussing solutions. Although, expert no. 2 clarifies that when the question of general accessibility as well as accessibility in relation to building services arises, existing design reviews is shortcoming.

Based on 2D drawings it is difficult to comprehend the constructability, according to expert no. 1. With a VR view of the building site it is easier to see how the work should be executed. Furthermore, a BIM model contains a large amount of information, which is lost in a 2D drawing. He states:

"With a 3D model one can see, how the design of building service system is intended"

Among other things the job descriptions as a project manager for the contractor, includes overall responsibility as well as design review. However, the project manager does not always hold knowledge of the various disciplines within building services, which can make it difficult to completely understand the intended design. For example, Expert no. 3 mentions that it is quite common for him to think, that there is enough space available for the ventilation system, but later he finds outs that there isn't, because he didn't focus on the different discipline, e.g. where the electrical engineer has placed the lighting units. He continues and adds, that VR makes it possible to observe the building services intuitively as in the real world, which gives him an ocular proof.

As an example, during the VR walk through a student's digital model, see Fig. 2, he noticed that a ventilation duct is modified from circular to rectangular, which is designed in order to keep the suspended ceiling at a certain level. Straight away he commented, that solution is way too expensive in the real world. Furthermore, he states that VR would make it possible to make a digital mock-up as an alternative to a physical mock-up, which is costly.

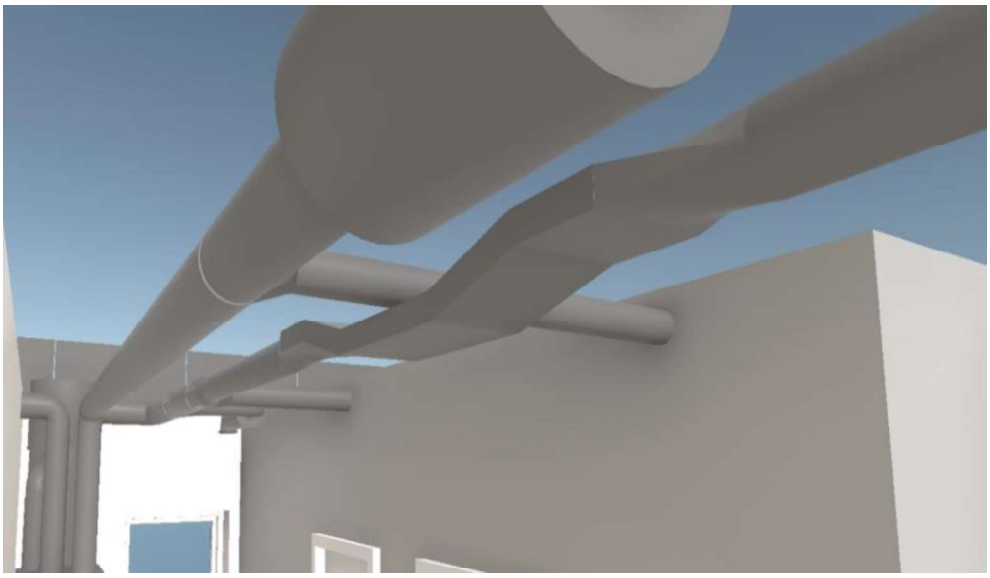

Fig. 2: VR view of a ventilation system proposal in an apartment. The proposal is designed by a team of AEC students during the convention, The Digital Days, in Aalborg (De Digitale Dage, 2018).

3.3.2 Which functionalities beneficial for a AR and VR setup?

A VR and AR setup makes it possible to access information from BIM. However, as the experts argue, an overflow of information makes it difficult to comprehend and understand a design. The key word is to keep it as simple as possible. Therefore, it is important to limit the amount of information to the appropriate level, in that way the user does not get disturbed.

Expert no. 4 argues that the information needed will vary depending on the user. E.g. when a contract manager uses the VR or AR technology, in contrast to the ventilation fitter, he does not need to know what type of hinge is used and the distance between the them. Therefore, it would be beneficial to include a user type, where type of information accessible is predefined based on who uses it.

Expert no. 3 argues that the level of information will also vary depending on the complexity as well as the type of the project. E.g. when building a hospital in contrast to a university faculty, different information is needed. Furthermore, when buildings are certified in according to a sustainability assessment standard, such as DGNB, additional requirements are set to the building services. In such a case expert no. 3 mentions, that he, as a project manager, would benefit from more specific information, such as information regarding the building automation system. Therefore, it would be beneficial to customize the amount of information, depending on the project as well as the user.

In the earlier mentioned design review meetings, between the different parts across the AEC industry, the failures and defects can be managed and taken care of in real time. However, in other cases, e.g. when a contract manager identifies failures and defects on site, it is important to manage them in a useful and intelligent way. For example, expert no. 3 mentions one should be able to take a picture in the virtual environment including a message describing the problem. Furthermore, the message should also include the position in relation to the 3D model, so that the receiver knows where the issue is. The problem should be appointed to a specific user, who then will get a notification. According to expert no.1 traceability, as described above, in the information flow is the key to good management

4. DISCUSSION

The results show, that failure and defects in the Danish AEC industry are genuine problems, which is also emphasized in existing studies (Akin, 2011; Hansen and Aagaard, 2013; Aagaard, Brunnch-Nielsen and Hansen, 2014). Furthermore, it shows that defects and failure is often related to building services, which is also concluded by others (Shirkavand, Lohne and Lædre, 2016; Thuesen and Ryesgaard, 2018). Moreover, complex buildings increase the complexity of building services. This entail more failures and defects, which also is the impression of Shirkavand et. al.

The experts agree that both VR and AR have the potential to improve the design review processes, which is also estimated by Bademosi and Issa (Bademosi and Issa, 2018). VR makes it possible to experience the 3D model of the building in scale 1:1 long before it is constructed. Furthermore, AR is a similar technology that overlays virtual 3D models and information on the physical world. This gives completely new opportunities to show where and how the building services should be placed in the carcass. As described in 3.3.1. two of the interviewed experts argue that an existing design review in 3D is an efficient method to reduce failures and defects in the design phase. However, significant failures and defects are still a well-known problem in the AEC industry (Akin, 2011; Thuesen and Ryesgaard, 2018). Furthermore, a study by Shikavand et al. imply that incomplete and poor design is the main reason for defects in building services (Shirkavand, Lohne and Lædre, 2016). Moreover, Lin et al. find that a virtual environment based discussion in the AEC industry, is more effective than traditional. Therefore, the authors suggest VR supported design review in the design phase and AR- in the construction phase, see Fig. 3. Seeing that existing design review involve regularly coordination meetings and quality control at the end of design and construction phase, it is suggested that VR and AR technologies are put in to use here (Lin *et al.*, 2015). It is also suggested that VR supported design review is used instead of a physical mock-up and to evaluate the constructability of building services.

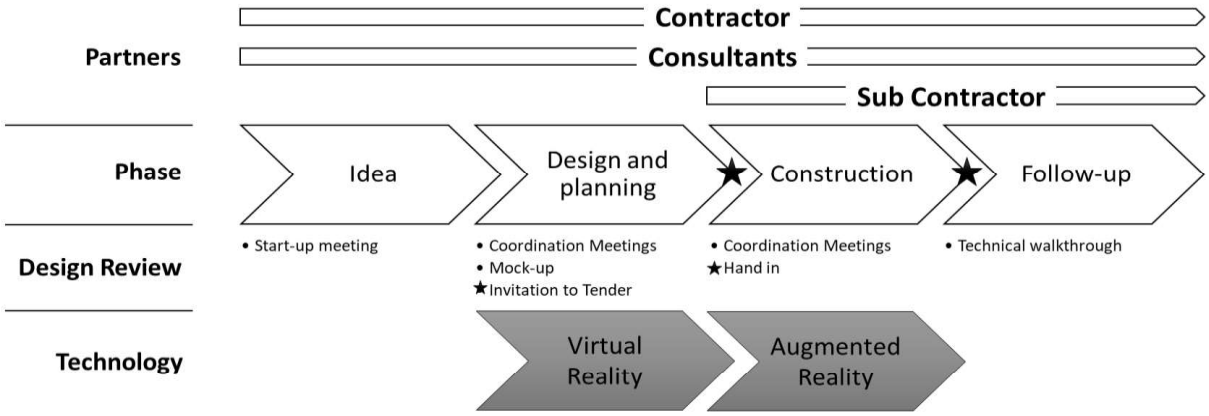

Fig. 3: Overview of a turnkey contract, showing which and where the identified, traditional design reviews are located and where VR and AR could be introduced.

An overflow of information can make it difficult to comprehend and understand a design. The results of this study indicate, that the information needed in an AR and VR supported design review will vary depending on the user and the complexity as well as the type of the project. BIM-based collaboration between experts of different disciplines, that requires appropriate model views that match their specific needs, is a known problem. Windisch et. al. suggest a filtering framework, that enables generation of various model views for a wide range of domains, tasks and applications in a consistent manner (Windisch, Katranuschkov and Scherer, 2012). This study suggests a similar information filtering process for the AR and VR setup, that is controlled by the identified parameters, see Fig. 4

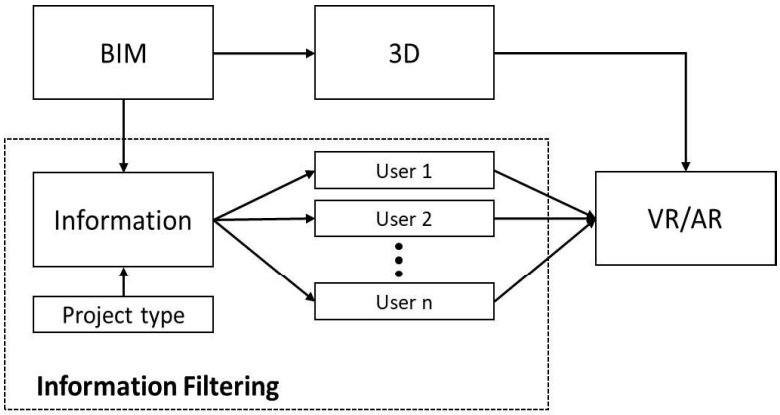

Fig. 4: An initial overview of an information filtering process in the VR and AR setup, that is controlled by the identified parameters.

5. CONCLUSION

The aim of this study was to identify possibilities for new VR and AR supported design review, that potentially can improve the quality of building services. The study was based on a qualitative study with semi-structured interviews of five representative experts from the AEC industry in Denmark. The main findings where:

- *Failures and Defects*: As indicated in existing research, the experts acknowledge that failures and defects in the AEC industry is a genuine problem. The more complex the building is, the bigger risk for mistakes. The problem often lies with building services, the experts appoint installations room, shafts, suspended ceiling and branch points. Furthermore, the experts agree that failures and defects arise both in design- and construction phase.

- *The Cause*: The failures and defects are often caused due to lack of collaboration between the different parts of the AEC industry, as well as lack of interdisciplinary collaboration between the different disciplines of building services. Furthermore, majority of contractors and subcontractors still use 2D drawings on site during the construction phase, which makes it difficult to comprehend.
- *Traditional Design Review*: Design review takes place during all phases. This could be individually or collaboratively between the different disciplines of building services as well as other parts of the AEC industry. This could be regularly coordination meetings as a part of an internal quality control or quality control before a handover. In the design phase, design review is typically carried out directly in BIM, whereas in the construction phase design reviews is typically carried out on the basis of 2D drawings.
- *VR and AR supported Design Review*: The experts agree that both VR and AR have the potential to improve design review of building services. Particularly, AR supported design review in the construction phase arouse an interest for the experts, since the technology is able to show virtual models and information on top of the physical world, which makes it possible to show how and where building services are to be placed in the carcass. On the other hand, two of the experts were less convinced about VR supported design review, since existing tools automatically detect collisions. However, if it's a question of constructability, such VR supported design review might come in handy. Furthermore, VR can potentially replace physical mock-ups.

This paper suggests a VR supported design review in the design phase and an AR supported design review in the construction phase, which takes place in the already existing design review, such as regular coordination meetings. Furthermore, an information filtering process for the VR and AR setup that is controlled by the project's complexity, type and user, is suggested.

Based on a semi structured interview, this study aims to identify new VR and AR supported design review processes. The interviews were conducted during DD, which entail that the selection of participants for the study was limited to experts from the Danish AEC industry. Due to the following reasons the conclusions given in this paper should not be seen as general, but rather indicative, as 1) the study is based on 5 interviews; 2) respondents consist of experts form the Danish AEC industry and 3) experts participating at a convention, such as DD, may in general be in favor of new technologies, such as VR and VR. Furthermore, our results especially in relation to the VR and AR shows an indication, as 1) the expert's knowledge within VR and AR was diverse and 2) the expert were asked to relate to the potential of VR and AR supported design review.

In our opinion, this study achieves to identify how VR and AR can support design review of building services. However, based on the limitations, future work should include a study of a more conceptualized VR and AR supported design review, that is based on a mix of qualitative and quantitative study. This could lead to a more in-depth understanding of how such a design review should work in practice as well as the effect of such an approach.

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